

Improved Electroweak Phase Transition with Subdominant Inert Doublet Dark Matter

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The inert doublet dark matter model has recently gained attention as a possible means of facilitating a strongly first order electroweak phase transition (EWPT), as needed for baryogenesis. We extend previous results by considering the regime where the DM is heavier than half the Higgs mass, and its relic density is determined by annihilation into W, Z and Higgs bosons. We find a large natural region of parameter space where the EWPT is strongly first order, while the lightest inert doublet state typically contributes only 0.1 – 3% of the total dark matter. Despite this small density, its interactions with nucleons are strong enough to be directly detectable given a factor of 5 improvement over the current sensitivity of XENON100. A 10% increase in the branching ratio for Higgs decays to two photons is predicted.

Introduction. The idea that the matter-antimatter asymmetry was created during the electroweak phase transition (EWPT), by the process known as electroweak baryogenesis (EWBG), is appealing because it is perhaps the only proposed mechanism of baryogenesis that can be directly tested at currently accessible energies in particle collider experiments [1, 2]. The subject has enjoyed a resurgence of interest since the advent of the Large Hadron Collider (LHC). It is well-established that new physics is needed to create a sufficiently strongly first-order phase transition [3, 4], which is one of the requirements for baryogenesis in this framework. Supersymmetry was the most-studied option for EWBG during the LEP (Large Electron Positron collider) era [5–14], but since the LHC has so far not found any evidence for supersymmetry, nonsupersymmetric extensions have received more attention recently. Moreover, new physics is also required to explain the dark matter (DM) of the universe, so it is natural to inquire whether the same ingredients might explain both DM and EWBG [15–25].

Recently there has been interest [22–28] in scalar dark matter models with respect to their potential for enhancing the electroweak phase transition strength. In the case where the scalar S is an electroweak doublet, it is “inert” due to the Z_2 symmetry $S \rightarrow -S$ that prevents it from coupling to fermions, and which stabilizes the lowest mass component against decay. Its couplings to the usual Higgs, of the schematic form $|H|^2|S|^2$, can give rise to a strengthened EWPT as desired for EWBG. However in the examples of the inert doublet model studied so far, fine-tuning of the dark matter mass with respect to the Higgs boson mass, $m_{\text{DM}} \cong m_h/2$, was needed in order to have a strong enough annihilation cross section

for achieving the right relic density (via resonantly enhanced by Higgs exchange in the s -channel), while simultaneously getting a strong enough phase transition [26]. Moreover in these cases a second fine-tuning between different $|H|^2|S|^2$ -type quartic couplings was needed, to keep the effective DM-Higgs interaction small enough to satisfy constraints from direct detection experiments, notably XENON100.

In the present work, we show that the parameter space for a strong EWPT plus potentially detectable inert doublet DM is significantly enlarged when we take into account heavier DM annihilations into W, Z and Higgs bosons, and if we allow for it to be a subdominant component of the full DM population. For these new examples, the fine-tuning problems mentioned above are eliminated, making this a more natural scenario. Even though inert doublet DM may constitute only 0.1% of the total dark matter in these examples, its interactions with nuclei, mediated by the Higgs, can be sufficiently strong to make it detectable with only modest improvements relative to the current sensitivity of XENON-like experiments. Such improvements are expected in the near future, making this proposal highly testable.

Model and Methodology. The potential of the inert doublet model is taken to be

$$V = \frac{\lambda}{4} \left(H^{\dagger i} H_i - \frac{v^2}{2} \right)^2 + m_1^2 (S^{\dagger i} S_i) + \lambda_1 (H^{\dagger i} H_i) (S^{\dagger j} S_j) + \lambda_2 (H^{\dagger i} H_j) (S^{\dagger j} S_i) + [\lambda_3 H^{\dagger i} H^{\dagger j} S_i S_j + \text{h.c.}] + \lambda_S (S^{\dagger i} S_i)^2 \quad (1)$$

The combination of couplings relevant to the dark matter candidate (by convention taken to be the CP-even neutral member H_0 of the S doublet) is

$$\lambda_{\text{DM}} = \lambda_1 + \lambda_2 + 2\lambda_3 \quad (2)$$

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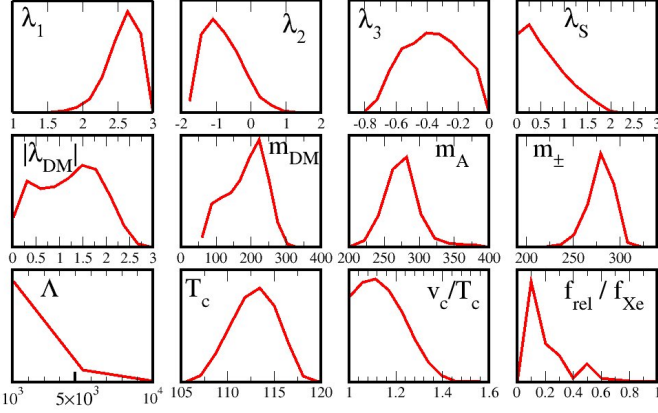


FIG. 1: Distributions of model parameters (both input and derived) from Monte Carlo. Dimensionful parameters are in units of GeV.

It controls both the DM mass, $m_{\text{DM}}^2 = m_1^2 + \frac{1}{2}\lambda_{\text{DM}}v^2$, where $v = 246$ GeV is the Higgs VEV, and the coupling to the real Higgs field h , $\frac{1}{4}\lambda_{\text{DM}}h^2s^2$. In the following we will take the one-loop correction to the zero-temperature effective potential to be augmented by counterterms that preserve these tree-level relations.

We use the same one-loop effective potential at finite temperature as described in ref. [26] for the analysis of the phase transition. We also apply the same accelerator mass, vacuum stability and electroweak precision data constraints as described there, as well as fixing the Higgs mass to be 126 GeV [29–32]. Where we depart from ref. [26] is in our treatment of the annihilation cross section that determines the H_0 relic density. In ref. [26], only annihilations to standard model fermions up to the b quark were included. Here we use a similar expression as in ref. [28], that includes more possible channels, notably into W and Z gauge bosons and higgs bosons, whose importance for DM-analysis was first observed in ref. [33]. We further extend the range of possible DM masses here to include annihilation into top quarks.

The annihilation cross section $\langle\sigma v\rangle$ is used to determine the relic density by comparing to results of ref. [34], where the value $\langle\sigma v\rangle_0$ that produces the full relic density, as a function of dark matter mass, was accurately computed. We define the fraction of the full relic density attributable to the inert doublet component as $f_{\text{rel}} = \langle\sigma v\rangle_0/\langle\sigma v\rangle$. We define another ratio $f_{\text{Xe}} = \sigma_{\text{Xe}}/\sigma_{\text{SI}}$ which involves the cross section for inert doublet scattering on nucleons, σ_{SI} , as given in ref. [35] (see ref. [28] for details of the Higgs coupling to nucleons), and the 2012 limit of XENON100 [36] σ_{Xe} . If the IDM scalar constituted 100% of the dark matter, the XENON100 limit would be that $f_{\text{Xe}} > 1$. But due to the subdominant density of this component, the constraint is relaxed to $f_{\text{rel}} < f_{\text{Xe}}$. We demand that this be satisfied, in addition to the relic density constraint $f_{\text{rel}} < 1$.

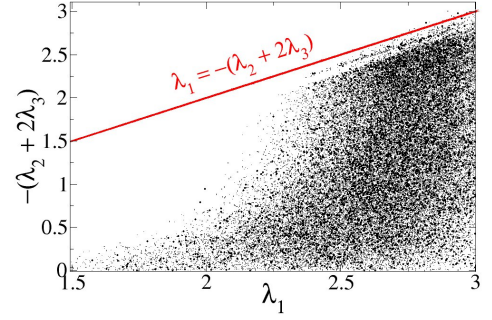


FIG. 2: Correlation between $\lambda_2 + 2\lambda_3$ and λ_1 , showing the absence of fine tuning $\lambda_1 = -(\lambda_2 + 2\lambda_3)$ which would be present if λ_{DM} was required to be small.

Monte Carlo results. We generated tens of thousands of models using a Markov Chain Monte Carlo (MCMC) procedure in which $(v_c/T_c)/\lambda_{\text{DM}}$ was the quantity chosen to be biased toward larger values, thus favoring both stronger phase transitions and smaller λ_{DM} at the same time. The latter criterion was not necessary for our purposes, since ultimately small values of λ_{DM} were still disfavored, but it was instructive to try to enhance the probability of such models in order to better illustrate the contrast between the large- λ_{DM} and small- λ_{DM} regimes. In previous studies, small values of λ_{DM} were required in order to sufficiently suppress the direct detection cross section. In the present work we find that larger values of λ_{DM} can be consistent with XENON constraints due to the suppressed relic density.

Distributions of parameters resulting from the Monte Carlo run are plotted in Fig. 1. These include the quartic couplings of the potential, λ_{DM} , the three scalar masses m_{DM} , m_A and m_{\pm} of the inert doublet, the scale Λ of the nearest Landau pole from running of the renormalization group equations, the critical temperature T_c , the measure v_c/T_c of the phase transition strength, and the ratio $f_{\text{rel}}/f_{\text{Xe}}$ that shows how close the model comes to saturating the XENON100 direct detection limit. It is seen that the magnitudes of the quartic couplings are typically $O(1)$ to get a strong phase transition, as expected. But in contrast to previous studies, there need no longer be a conspiracy amongst large couplings to make the combination λ_{DM} in eq. (2) small. This absence of tuning is further demonstrated by Fig. 2, that shows most of the accepted models are not clustered around the relation $\lambda_1 = -(\lambda_2 + 2\lambda_3)$ as was the case in ref. [26].

The distributions in Fig. 1 show a preference for the masses $m_{\text{DM}} \sim 200$ GeV and $m_A \sim m_{\pm} \sim 280$ GeV. This is further illustrated by the scatter plots of Fig. 3, showing correlations of masses m_{\pm} and m_A and of f_{rel} versus m_{DM} . These reveal narrow islands of $m_{\text{DM}} \sim m_h/2$ that correspond to the finely-tuned case of resonant enhancement of DM annihilation with Higgs in the s channel. This allows the relic density to be suppressed despite having $\lambda_{\text{DM}} \ll 1$ in order to satisfy direct detection constraints, and was the case focused upon in ref. [28]. Here we see that these regions now constitute only a small frac-

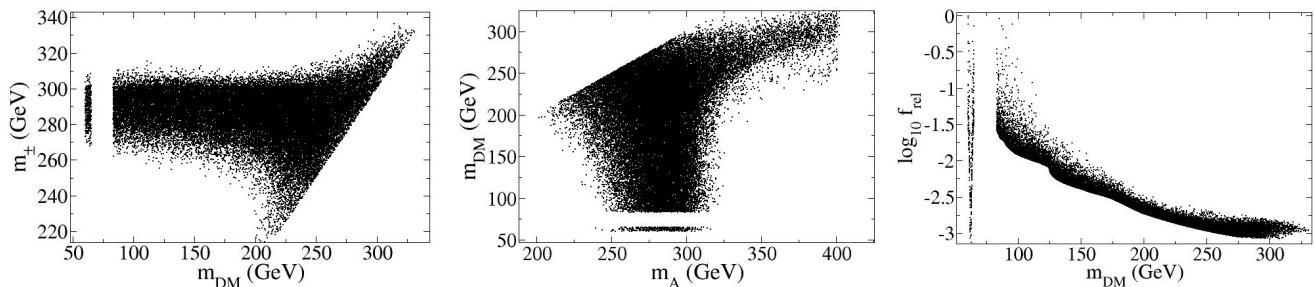


FIG. 3: Panels from the left to right: the correlation between the dark matter mass m_{DM} and the charged scalar mass m_{\pm} (1), between m_{DM} and the CP-odd neutral scalar mass m_A (2) and between m_{DM} and the logarithm of the fraction of the full relic density $\log_{10} f_{\text{rel}}$ (3).

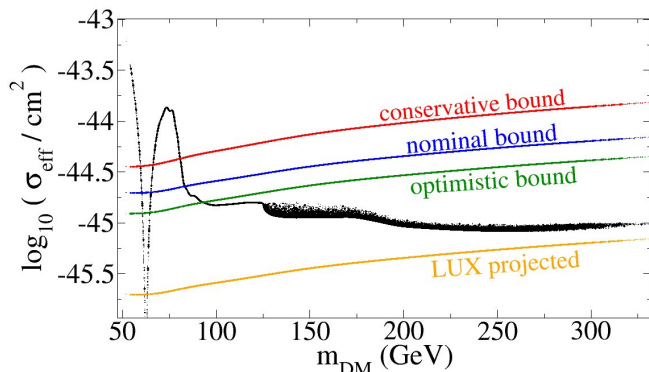


FIG. 4: The scatter of the expected cross section for direct detection vs. m_{DM} . Central curve (blue) shows the nominal XENON100 bound [36] and the upper and lower (red and green) lines respectively are the more conservative/optimistic bounds reflecting uncertainties due to local DM distribution. Bottom curve is expected constraint from LUX experiment.

tion of our sample, which was enhanced by our choice of $(v_c/T_c)/\lambda_{\text{DM}}$ rather than (v_c/T_c) as the quantity to be maximized by the MCMC. There is a gap in the region $m_h < m_{\text{DM}} < m_W$ because the annihilation cross section below the threshold for W-pair production is too small to achieve a low enough relic density for these DM masses.

Fig. 1 shows that the cutoff Λ tends to be only a few TeV, indicating that this is an effective theory which must be UV-completed by additional new physics at a relatively low scale. The enhancement in the phase transition strength is modest, $v_c/T_c < 1.5$, but still sufficient for electroweak baryogenesis. The ratio $f_{\text{rel}}/f_{\text{Xe}}$ tends to be small, but can easily exceed 0.2, say, indicating that such models will be discoverable by direct detection in XENON-like experiments given a 5-fold increase in sensitivity. This is also illustrated in Fig. 4, which shows the distribution of the accepted models in the plane of m_{DM} versus the effective interaction cross section $\sigma_{\text{eff}} \equiv f_{\text{rel}}\sigma_{\text{SI}}$, which takes into account the reduced sensitivity of direct detection experiments due to the subdominant nature of the dark matter. The lower curve is our estimate of the bound which is anticipated to be set by the LUX experiment [37]; we simply assumed that the m_{DM} -dependence of the constraint is the same

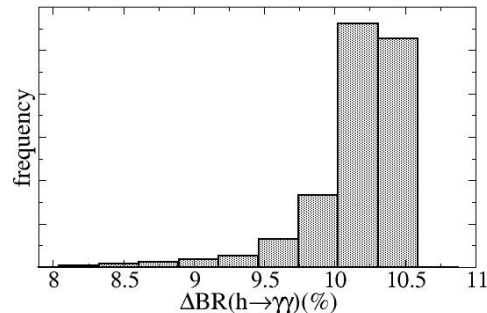


FIG. 5: Distribution of changes in the branching ratio for $h \rightarrow \gamma\gamma$ decays relative to the standard model prediction, for models generated by the MCMC.

as that of XENON100, scaled by anticipated LUX limit of $\sigma < 2 \times 10^{-46} \text{cm}^2$ at $m_{\text{DM}} = 40 \text{ GeV}$ [38]. This is expected to be achieved in 2013; thus our proposal will be tested over its entire relevant mass range in the very near future.

As for the overall density of the inert DM component, the rightmost graph of Fig. 4 shows that only a few finely-tuned models with m_{DM} close to m_h , or to the m_W threshold, have Ω_{DM} close to the observed value. The majority of models have $10^{-3} \lesssim f_{\text{rel}} \lesssim 0.03$.

In ref. [28] it was noted that due to contributions of the charged Higgs, a 10% increase in the branching ratio for Higgs decays to two photons, relative to the standard model expected value, was predicted for the models of interest. There are experimental hints of an excess in this channel from ATLAS [39] and CMS [40]. We find that the earlier prediction of a 10% enhancement is unchanged despite the larger region of parameter space available in the present scenario. The distribution of the percent change in the branching ratio for $h \rightarrow \gamma\gamma$ is shown in Fig. 5.

Conclusions. We have shown that it is in general easy to find a strongly first order phase transition, desirable for electroweak baryogenesis, in the context of inert doublet models that also provide some fraction of the observed dark matter. The lightest inert doublet state is found to typically contribute 0.1 – 3% of the total

dark matter. Its interactions with nucleons are nevertheless strong enough to be directly detectable given a factor of 5 improvement over the current sensitivity of XENON100, which is expected to be achieved this year by LUX. Moreover, we showed that the model predicts a 10% increase in the branching ratio for Higgs decays to two photons. We did not attempt to compute baryon asymmetry that might be achieved in this model. To do so, one should introduce a source of CP-violation in the fermion sector, for example a dimension-6 operator contributing to the top quark mass, of the form $\eta|H|^2\bar{t}Ht$ with complex coupling η , and numerically evaluate the Boltzmann equation network for chemical potentials of

chiral quark species near the electroweak bubble walls that form during the phase transition. Based on experience from similar studies elsewhere [28, 41], it seems possible that the model augmented in this way could produce the observed baryon asymmetry of the universe. If dark matter is directly detected in the 100-300 GeV mass range, we will be encouraged to pursue this further.

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